Edge on Impact Simulations and Experiments

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14. ABSTRACT

In the quest to understand damage and failure of ceramics in ballistic events, simplified experiments have been developed to benchmark behavior. One such experiment is known as edge on impact (EOI). In this experiment, an impactor strikes the edge of a thin square plate, and damage and cracking that occur on the free surface are captured in real time with high speed photography. If the material of interest is transparent, additional information regarding damage and wave mechanics within the sample can be discerned. Polarizers can be used to monitor stress wave propagation, and photography can record internal damage. This information serves as an excellent benchmark for validation of ceramic and glass constitutive models implemented in dynamic simulation codes. In this report, recent progress towards predictive modeling of EOI is discussed. Time-dependent crack propagation and damage front evolution in silicon carbide and aluminum oxynitride ceramics are predicted using the Kayenta macroscopic constitutive model. Aspects regarding modeling material failure, variability, and volume scaling are noted. Mesoscale simulations of dynamic failure of anisotropic ceramic crystals facilitate determination of limit surfaces entering the macroscopic constitutive model, offsetting limited available experimental data.

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Edge on Impact Simulations and Experiments

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Abstract

In the quest to understand damage and failure of ceramics in ballistic events, simplified experiments have been developed to benchmark behavior. One such experiment is known as edge on impact (EOI). In this experiment, an impactor strikes the edge of a thin square plate, and damage and cracking that occur on the free surface are captured in real time with high speed photography. If the material of interest is transparent, additional information regarding damage and wave mechanics within the sample can be discerned. Polarizers can be used to monitor stress wave propagation, and photography can record internal damage. This information serves as an excellent benchmark for validation of ceramic and glass constitutive models implemented in dynamic simulation codes. In this paper, recent progress towards predictive modeling of EOI is discussed. Time-dependent crack propagation and damage front evolution in silicon carbide (SiC) and aluminum oxynitride (AlON) ceramics are predicted using the Kayenta macroscopic constitutive model. Aspects regarding modeling material failure, variability, and volume scaling are noted. Mesoscale simulations of dynamic failure of anisotropic ceramic crystals facilitate determination of limit surfaces entering the macroscopic constitutive model, offsetting limited available experimental data.

Keywords: edge on impact, ceramics, damage, silicon carbide, aluminum oxynitride

1. Introduction

Traditionally, ballistic experiments have been used to parameterize macroscopic continuum ceramic models, in particular their evolution of damage. It is proposed here that simpler experiments, with less system response issues related to typical penetration experiments used in the past, could supplement traditional quasi-static experiments for ceramic material model calibration. Edge on impact (EOI) experiments [1, 2, 3] provide insight into dynamic damage velocities and failure morphology that should be resolved in accurate simulations of ballistic impact and penetration of armor ceramics. Additionally, suggested in this paper is a new approach whereby the limit surface for a ceramic material's macroscopic constitutive description is constructed from parametric mesoscale simulations, allowing rapid parameterization. This approach augments existing experimental data and reduces the number of expensive experiments used in calibration.

This paper is organized as follows. Relevant EOI experiments are reviewed in Sect. 2. Macroscale and mesoscale models of ceramic materials are summarized in Sect. 3. New model predictions of EOI of SiC and AlON targets are

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compared with experimental observations in Sect. 4. Concluding remarks follow in Sect. 5.

2. Experiments

EOI experiments were conducted by Strassburger et al. [1, 2, 3] at the Ernst Mach Institute (EMI), under a contract with the US Army Research Laboratory (ARL). Ceramic targets consisted of nominal 100×100×6 mm plates, impacted by steel cylinders or spheres. Various velocities and target materials were explored. Experiments on SiC (type B) and AlON are reported here. Nominal velocities for impact were ~50 to 1000 m/s. Cracking and damage were imaged using a 24 spark Cranz-Schardin high-speed camera. A damage velocity was calculated by dividing the maximum distance of crack initiation and failure, measured from the impact center, by the time from initial impact. Damage velocities increased as impact velocities increased, approaching the longitudinal wave speed of the ceramic.

Figure 1 shows a drawing of the experiment and the experimental method by which damage velocities were determined. In this example (AlON impacted at 400 m/s), a series of pictures was taken, and the damage front was measured radially from the origin at the impact point. For a transparent material with a large grain size like AlON, crack initiation points and the defect distribution can readily be seen. A similar technique was used for opaque SiC, restricted to the visible free surface for visualization of damage propagation.
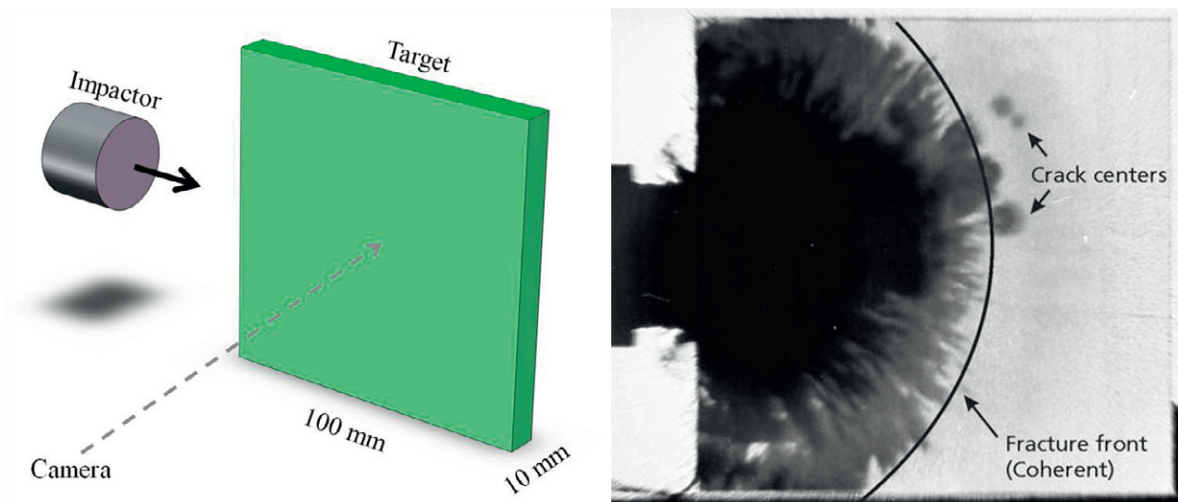

Fig. 1. Edge On Impact (EOI) drawing (left), and experiment in AlON (right), showing the method for fracture front (damage velocity) measurement.

2.1. Silicon Carbide

SiC is an opaque ceramic explored by the armor community. It is perhaps the most extensively characterized material for armor ceramic model development, and demonstrates behaviors typical of many armor ceramics: high hardness, high elastic stiffness, low mass density, and low ductility relative to steels, with stochastic strength dependent on pressure, loading rate and history, and sample size. The ceramic used in these tests was produced by CERCOM using a process of pressure assisted densification. The typical grain size was ~ 5 μm.

Steel cylinders with a diameter of 30 mm and a length of 23 mm were used in the EOI experiments. Side faces of the ceramic were polished to a mirror-like finish, to improve visualization of cracks on the surface [3].

2.2. Aluminum Oxynitride

AlON of adequate purity is transparent and has a large grain size (~ 200 μm), useful features for connecting macro- and mesoscopic simulation length scales. Experimentally, being able to see within the target promotes further understanding of mechanisms of time-dependent failure propagation [4].

AlON targets were impacted with spheres and cylinders in the velocity range ~250 to 950 m/s. Pressure-induced dark sections in the images are visible due to changes in the index of refraction of the material, in addition to actual damage and fracture. Given the optical properties of AlON, light can be transmitted through the specimens as well, with cross-polarizers

detecting the stress wave front in front of the damage front [2].

3. Modeling and Simulation

3.1. Kayenta Model

Kayenta [5] is a generalized plasticity model used to describe ceramics at the macroscopic continuum level. The limit surface of a material element essentially describes the three-dimensional stress state-dependent mechanical response of that element. Experimental data are used as available to parameterize the limit surface for SiC. Limit surface evolution is witnessed in results reported later in Sect. 4. Kayenta allows for third invariant dependence, softening, hardening, and porosity. The theory incorporates evolution of variability and volume scaling as witnessed in calibration experiments, to improve predictive capabilities of simulations. Currently, a Weibull distribution describes variability of material strength in hydrostatic tension. This variability is scaled based on the local finite element size, with a time-to-failure criterion allowing damage to propagate at the same speed, regardless of element size.

Leavy et al. [6] provide details on the Kayenta model formulation and its parameterization for SiC. In addition, forthcoming articles by Brannon et al. [7, 8] give more details on the statistical nature of the Kayenta model and its underlying theory.

In this paper, a new method of Kayenta model parameterization is reported. In the absence of sufficient experimental data to accurately characterize AlON, mesoscale simulations of various simple load paths are used to map the limit surface for the macroscopic (Kayenta) model.

3.2. Mesoscale Model

Mesoscale simulations were conducted on both SiC and AlON polycrystals, as reported in detail elsewhere [9, 10]. A brief summary of the approach is given here, along with relevant findings for AlON that are directly incorporated into macroscale simulations reported later in Sect. 4.2.

Behavior of single crystals within each grain is addressed using standard anisotropic nonlinear hyperelasticity [11, 12], with a third-order internal energy potential

$$U = \frac{1}{2} C_{IJKL} E_{IJ} E_{KL} + \frac{1}{6} C_{IJKLMN} E_{IJ} E_{KL} E_{MN} , \tag{1}$$

where C_{IJKL} and C_{IJKLMN} are isentropic second- and third-order elastic constants; in the absence of experimental data, the latter are estimated [13, 14] from pressure derivatives of tangent moduli computed in first principles (quantum or atomic) simulations. Green-Lagrange strain is $E_{IJ} = \frac{1}{2}(F_{iI} F_{iJ} - \delta_{IJ})$, with $F_{iJ} = \partial x_i / \partial X_J$ the deformation gradient.

Intergranular fracture is addressed via a cohesive zone model [9, 10, 15], wherein the surface energy of separation

$$\gamma = \frac{1}{2} \tau \Delta = \frac{K^2 (1 - \nu^2)}{2E}, \tag{2}$$

with τ the fracture strength, Δ the separation distance beyond which no tensile or shearing resistance is supplied, K the fracture toughness, ν the Poisson ratio, and E the Young's modulus. Fracture model parameters for pure normal and pure tangential separation are assumed identical. As a first approximation, interfaces are assigned uniform properties obtained from macroscopic polycrystalline fracture toughness and flexure strength experiments. After complete separation, grains interact via sliding contact. Two grain geometries with tetrahedral finite element meshes were supplied by Kraft et al. [15].

Mesoscale simulations were executed using the SIERRA explicit dynamics code [16] with an imposed strain rate of 10^5 s^{-1}. Uniform velocity gradient initial conditions were implemented to prevent generation of a shock during initial loading. Therefore, these simulations differ from traditional plate impact or shock compression, providing a more homogeneous stress state that may be more realistic for extracting average behavior in a multiscale modeling context. Approximately 90 simulations were executed for each material, considering two different grain geometries, various orientations of the polycrystal volume element with respect to the loading direction, various random orientations of the crystal lattice of each grain in the polycrystal, and three general kinds of boundary conditions: uniaxial strain compression, uniaxial stress compression, and shear. For shear simulations, compressive stress states were superimposed in some cases. Axial Cauchy stress σ is shown in the left in Fig. 2 for a uniaxial strain compression simulation of an AlON polycrystal consisting of 50 grains, deformed to 5% compression (i.e., V/V_0=0.95). Compressive loading is parallel to the X-direction, and the stress component shown is the XX component of Cauchy (true) stress. The specimen is constrained from expanding laterally in

the Y- and Z- directions, but is free of shear traction on these faces. Macroscopic shear strength versus pressure data from numerous simulations are fit to a form of strength model [6] used in Kayenta in the right part of Fig. 2.
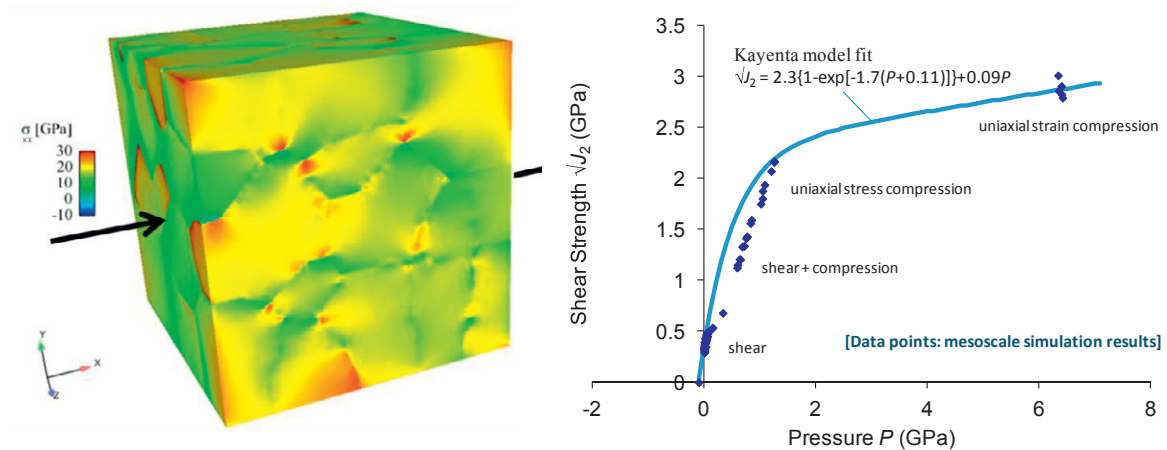

Fig. 2. Mesoscale simulation of AlON, showing stress concentrations generated during dynamic uniaxial strain compression (left), and shear strength versus pressure data from AlON polycrystal simulations and model fit used in Kayenta (right).

4. Results

Simulations of EOI were conducted using the Kayenta model in ALEGRA, a hydrocode developed at Sandia National Laboratories (SNL). In this application, the projectile and targets were modeled using Lagrangian elements. A rectangular block grid was used for the targets. Variability and volume scaling were used in the ceramic targets. Even though these methods are used to mitigate mesh dependency, a mesh dependent crack propagation orientation is evident in the fractured material which advances before the damage front. Work is underway to improve the volume scaling and damage evolution in the Kayenta model. Time dependent experiments which track damage evolution greatly enhance validation of continuum ceramic models. The present models were not parameterized or calibrated with these experiments in mind, save for the assumption of the AlON crack speed value. Previous ballistic impact experiments of confined ceramic targets were used to determine crack speeds and the Weibull modulus for SiC.

4.1. Silicon Carbide

Figures 3 and 4 compare experimental images with model predictions of EOI of SiC targets at respective impact velocities of 513 m/s and 1040 m/s. In the model predictions, colors denote time to failure [5] (blue to red ↔ 5 μs to 0 μs), and grayscale contours denote pressure. Damage propagation fronts as well as cracks preceding each front can be seen. In addition, spall and tensile failure on the back surface, as seen in the high velocity SiC impact in Fig. 4, are reproduced. At higher velocities, damage is more severe and propagates more rapidly. The ability of the simulations to reproduce damage morphologies, including spall, at various impact velocities and various time steps demonstrates validity of the Kayenta model and its parameters for SiC under dynamic loading conditions.

Experimental and simulation results for damage velocity versus impact velocity are shown in Fig. 5: the solid line is a logarithmic fit to experimental damage front velocity, and the dashed line a fit to simulation results at medium mesh resolution. For impacts above 370 m/s, simulation results for the damage front matched the experimental results; at lower velocities, simulations under predict the damage velocity, giving an average of 83% of the experimental results.

Damage velocities start to plateau to 90% of the longitudinal wave speed as impact velocity is increased. Experimentally, Strassburger [1] reported a crack speed of 3490±390 m/s. For Kayenta simulations, setting the crack speed to 30% of the longitudinal wave speed equates to 3685 m/s. Thus the constant crack speed used in simulations automatically handles rate effects and incorporates the required decrease in crack coalescence and damage propagation as impact velocity decreases. The coalescence of cracks and damage introduced by variability accounts for the damage velocities that are roughly three times the input crack speeds.

In addition, in a mesh convergence study of SiC impacted at 1040 m/s, damage front velocities increase with resolution.

Results differ at higher resolutions, implying that the volume scaling and variability do not exactly scale with the change in mesh size. This is probably due to the complex means by which the failed elements coalesce and merge to create the cracks and damage fronts. Variability and convergence of continuum damage models are areas that merit further study.
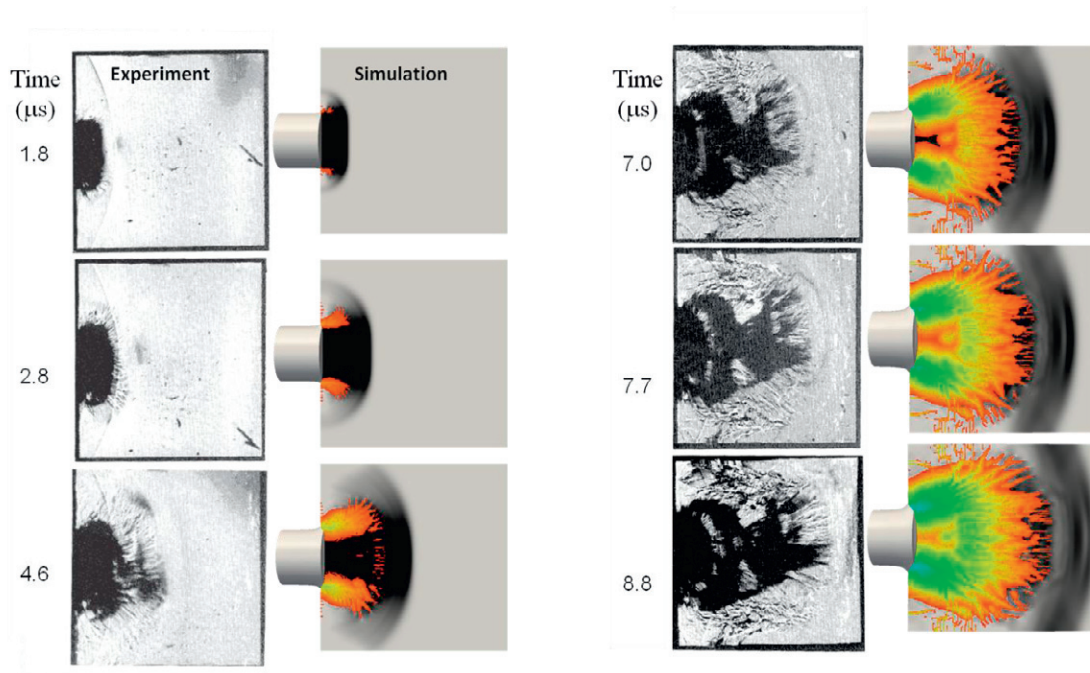

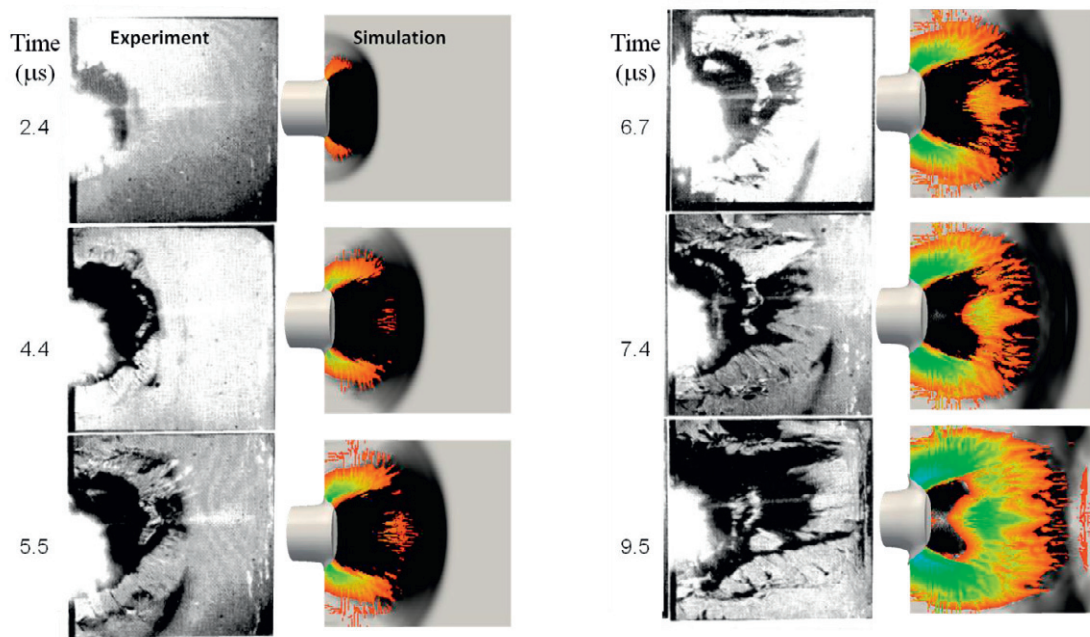Fig. 3. SiC EOI experiment and simulation at 6 timesteps, for a cylindrical impactor at 513m/s.

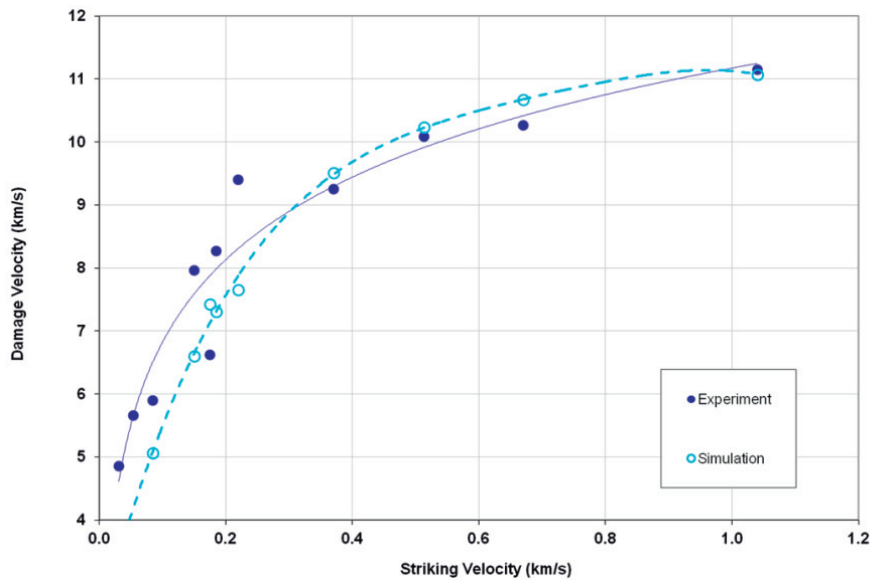Fig. 4. SiC EOI experiment and simulation at 6 timesteps, for a cylindrical impactor at 1040 m/s.

Fig. 5. Damage velocity from experiments and simulations of EOI of SiC.

4.2. Aluminum Oxynitride

The AlON Kayenta model is in its infancy, but some of the salient damage features have been revealed. AlON has been simulated with a crack speed that appears to be different from that of SiC: 10% of the longitudinal wave speed versus 30% for SiC. This would be one material parameter ideally determined using simplified crack generation experiments for all materials of interest. Insight into variability of AlON strength is also being explored. Simulation results shown in Fig. 6 for AlON use a Weibull modulus of 23.7, the value reported for static flexure experiments [17]. Simulations remain to be conducted with the lower Weibull modulus of 14.9 that was deduced from mesoscale simulations completed for AlON [9, 10]. The color scale for simulation results in Fig. 6 again reports time to failure.

The damage velocity experimentally determined by Strassburger [2] was ~8900 to 9800 m/s for AlON. Once again, the damage velocity was approximately 90 % of the longitudinal wave speed. For aluminum oxynitride, although simulations incorporated a substantially different crack speed of 10% of the longitudinal wave speed, a similar damage velocity resulted.

Both SiC and AlON impact simulations exhibited substantial mesh texture bias. Since a traditional Lagrangian hexahedral mesh was used, damage and cracking align in a preferential horizontal and vertical fashion. This is most noticeable in the AlON simulations impacted by spheres, in which crack branching and fanning that was seen in the experiment was inhibited somewhat in the simulations. Similar effects have been noted by Timmel et al. [18] with glass models. Although the variability and volume scaling helps mitigate these negative influences, these issues are still apparent.

Agreement between simulation and experiment for crack patterns is promising. The ability of the simulations to predict damage morphology and crack speeds similar to experiments at various impact velocities and various time steps demonstrates initial success of the Kayenta model for AlON. The present results also suggest that the limit surface used here for AlON constructed from existing mesoscale simulation data may be adequate for modeling EOI, though future improvements are anticipated that will address limitations in the mesoscale approach [10] and may provide additional insight into the macroscopic limit surface.

5. Conclusions

Ceramic material models at the macroscale and mesoscale have been discussed. Dynamic EOI experiments which highlight the complex failure mechanisms and damage propagation have been used to validate constitutive models in regimes of interest for terminal ballistics applications. EOI has been suggested as a simple alternative to ballistic penetration experiments for determining damage propagation speed. These experiments provide a simple means to assess failure of ceramic and glass materials, and provide further insight into the current limitations of ceramic models and simulation codes.
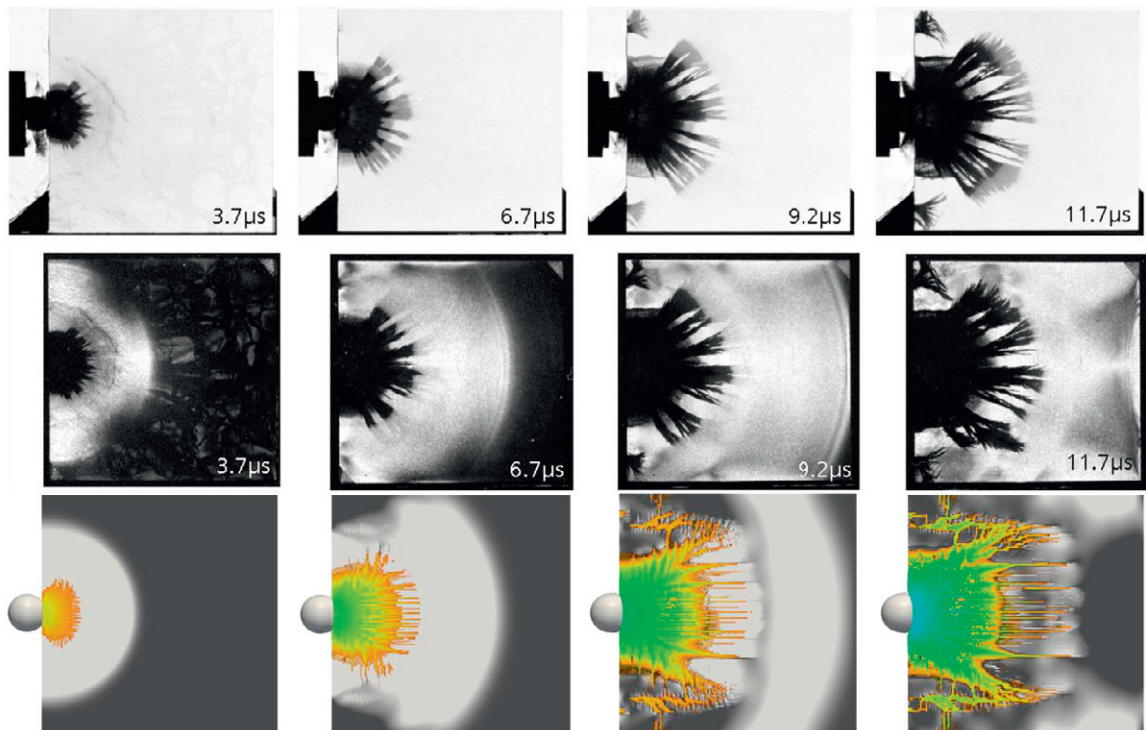
Fig. 6. AlON EOI experiment (top two rows) and simulation (bottom row) at 4 timesteps, for a spherical impactor at 426 m/s.

Acknowledgements

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